Chapter 17
The Galician Rías. NW Coast of Spain

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17.1 Introduction

The rías on the coast of Galicia make up a series of deep sea inlets along the entire 1720 km long coastline. In plant view, their morphology is cone or funnel-shaped and features two distinct sectors: the first makes up the larger cone, which corresponds to the ría itself, and the second is the smaller cone corresponding to the river channel which discharges into the headwaters. Rías can be classified as drowned river valleys that were flooded by seawater after the last transgression, with rivers at their headwaters, all of which bring about conditions more typically seen in estuaries. They are also associated with a complex variety of sedimentary environments, such as bays, intertidal plains, deltas, marshlands, beaches and sand dunes.

The orientation of the rías is structurally controlled by a sub-continental basement fracture system related to the break-up of Gondwanaland. From a geological point of view, Galician rías trend north-eastward, nearly at right angles to the main north trending Palaeozoic structural trends. Its coast is characterized by an irregular morphology tectonically controlled by three main fault systems: NE-SW, ENE-WSW and N-S trending faults. These fracture systems control the orientation

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of the main longitudinal axis of most of the major rías, particularly those facing the Atlantic Ocean.

In the scientific literature, the terms estuary and ría have always been used interchangeably, and as a result many of the studies carried out on estuaries were similarly applied to rías, especially with regard to the sea and river water mixing processes (Boyd et al. 1992; Dalrymple et al. 1992). Nevertheless, today we know that rías are in fact different and that they have a more complex arrangement of environments, dominated by processes related to wave energy, in which estuarine areas can be clearly distinguished (Vilas et al. 2010).

Etymologically, the word "estuary" is derived from the Latin "aestuarium", meaning marshland or canal, which in turn is derived from the word "aestus", which means "tide". Therefore the term is applied to any coastal environment where the tide is particularly important. As a result, in the second half of the 14th century, the terms "ría" and "estuary" were used interchangeably and both referred to the part of the river at the sea outlet. There is a great variety of definitions, depending on the different fields which include the study of estuaries. Many are contradictory, due to the varying knowledge of researchers, or due to the specific characteristics of those bodies of water partially enclosed in a coastal area, which at the same time receive fluvial inputs. The criterion for the definition put forward by Pritchard (1952, 1967) is salinity, whereas Fairbridge (1980) takes into account how far the sea reaches into a river valley. Both definitions are complementary and they are also valid in so far as determining the upstream limits of salinity penetration, as well as of tidal penetration, and both work well for those estuaries linked to river mouths. Other definitions try to adapt to the different peculiarities that are present in different coastal inlets, such as coastal lagoons, which are only occasionally connected to the sea (Day 1980) or including a biological component (Perillo 1995). There are other varying definitions for the term 'estuary', depending on whether they emphasize physical, eustatic, tectonic or sedimentological criteria. Taking into account the latter, Dalrymple et al. (1992) establishes differences in the upper and lower limits of estuaries with regard to definitions based on salinity. He defines an estuary as "the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes. The estuary is considered to extent from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth". From a geomorphological point of view, the term "ría" is used by Perillo (1995), albeit to refer to a type of estuary and only in reference to those rías in which an area may be influenced by estuarine processes.

The term "incised valleys" has also been used in studies into the sedimentary fill of these environments (Dalrymple et al. 1994), given that these are areas where it is possible to identify the transgressive (TST) and the highstand sequence (HST), which, in general, fills the resulting incision during one lowstand-transgressive-highstand sequence.

As occurs in estuaries, the "rías" along the Galician coast are influenced by mechanisms such as variations of the tidal range (Davies 1964), the degree of energy dominating in different sectors and also the fluvial discharge into the

headwaters (Vilas and Nombela 1985; Vilas et al. 2005). An understanding of these environments makes it possible not only to characterize a specific environment, but also to interpret the various facies preserved in the fossil record. Furthermore, these are areas of high biological productivity and therefore subject to various economic and human activities; as a result, any information regarding their sedimentology and hydrodynamics is of great interest, due to variations in the sedimentary bottoms and their influence on the distribution of species.

17.2 The Term Ría

The term "ría" has a relatively old origin, according to the revision by Méndez and Rey (2000) and Méndez and Vilas (2005). It is found in the 1495 edition of a Spanish-Latin vocabulary by Elio A. de Nebrija, denoting a "river port, ostium fluminis". In 1780, the Royal Academy of the Spanish Language generalised its use to refer to a geographical area with a characteristic topography or morphology, defined as "the part of the river at the sea outlet". Later, Von Richthofen (1986) adopted the term "ría" to designate a type of coast characterized by the existence of a valley occupied by the sea, taking as an example the Galician rías. Numerous works appear once the term "ría" is introduced in the scientific literature. It is worth highlighting the cartographic works by Schurtz (1902), Scheu (1913), Torre Enciso (1958), geomorphological and tectonic works by Carlé (1947, 1949, 1950) and Nonn (1966), who establishes a morphological classification of the rías of the coast of Galicia, as well as the works by Pannekoek (1966a, b, 1970) in which he attributes the main characteristics of the relief of the rías coastline to the Hercynian faults reactivated during the Tertiary.

Other authors consider that the term "ría" should be restricted to specific coasts of the Iberian Peninsula coastline and other areas of high relief such as Brittany in France, Devon and Cornwall in the United Kingdom, Korea, Southeast China and the South of Patagonia in Argentina, among others (Castaing and Guilcher 1995; Goudie 2018). In his review of the term "estuary", Perillo (1995) also establishes a similar definition, although he associates the term "ría" to an estuary developed in a river valley on a high relief coast, giving as an example the rías on the Galician coast, in contrast to the estuaries occupying low relief coasts, such as the Thames or the Gironde. However, there is a dilemma regarding this assessment, given that it contemplates the existence of estuarine circulation in both cases; in the case of the Galician rías, although they feature similar hydrodynamic processes, typical estuarine circulation is only present in the inner most area of the ría, namely where the river flows into the ría (Ruiz-Villarreal et al. 2002; Souto et al. 2003; Piedracoba et al. 2005; Vilas et al. 2005). Besides, the characteristics and distribution of sediment in rías (Rubio et al. 2001; Rey et al. 2005; Vilas et al. 2005) also display significant differences with respect to the facies models described for estuaries. Furthermore, several works carried out on the Galician coast to establish the genesis and evolution of the north-western sector of the peninsula (Vidal-Romaní 1996;

Twidale and Vidal-Romaní 1994; Vilas et al. 1995, 1996, 1999b; Pagés-Valcarlos 2000, among others), as well as the evolution of the Galician coastline since the last glacial maximum (García-Gil et al. 2002; Vilas et al. 2005; Muñoz-Sobrino et al. 2016; Gonzalez-Villanueva et al. 2015, among others) make it possible to consider the term ría in a broader sense than a simple geomorphological context, as considered by Evans and Prego (2003). Recently, the Spanish Royal Academy of Exact, Physical and Natural Sciences (RAC), in its Scientific and Technical-Geological Lexicon (Vera et al. 2013), defines the term "ría" as: "A flooded river valley, developed on a rocky coast, submerged as a result of a relative sea level rise. In plan view, it is shaped like a funnel with deep entrances. A cross-section view reveals a trough-like shape and a flat bottom, except nearest the head, where it has a V shape. Most of the surface presents marine conditions, with swell that controls the distribution of sediments (sands in the shallowest areas and lutite in the deepest). Actual estuarine processes are only present at the mouths of the rivers flowing into the ría."

Types of Rías

Taking into account only the most significant geomorphological features present in the rías on the Galician coast, Nonn (1966) establishes three types of ría (Fig. 17.1). The first corresponds to the lowest area of a drowned river system, where the river is responsible for the amplitude of the ría and often for the course. Nevertheless, alteration processes of the rock along the banks may also be involved or small-scale tectonic processes. It is on the Cantabrian shore of the North coast of Galicia where the best examples can be found (rías of Ortigueira, Barqueiro, Foz, Ribadeo) although it is also possible to identify partially similar examples on the northwest coast (rías of Cedeira, Ferrol, Ares and Betanzos, Laxe and Camariñas). The second type is characterized by the preponderance of tectonics and, above all, when it is impossible to justify the size of the rías based on their main rivers. Consequently, the hydrographic systems of the river Verdugo-Oitavén corresponding to the Ría of Vigo, that of the river Lérez in the Pontevedra Ría and of the river Tambre in the Muros and Noia Ría, according to Nonn (1966), demonstrate that the present-day volume of water does not justify the dimensions of these rías; as a result he concludes that tectonics (by means of subsidence, uplift and rotation of the tectonic blocks of the emerged part) are responsible for the configuration of this sector, where the rías are known as Rías Baixas. The third type corresponds to drowned basins altered during the Tertiary; these rías are reached by rivers of a certain importance, whose courses are developed during periods of low sea level. They feature a characteristic "globular or amoeboid" shape (divided into branches, when seen from above) and exemplified on the Galician coast by the rías of A Coruña and Arousa.

Despite all of the above, it is also possible to interpret the existence of rías with mixed characteristics, given that these different types are determined by the prevalence of certain mechanisms over others in order to establish this classification.

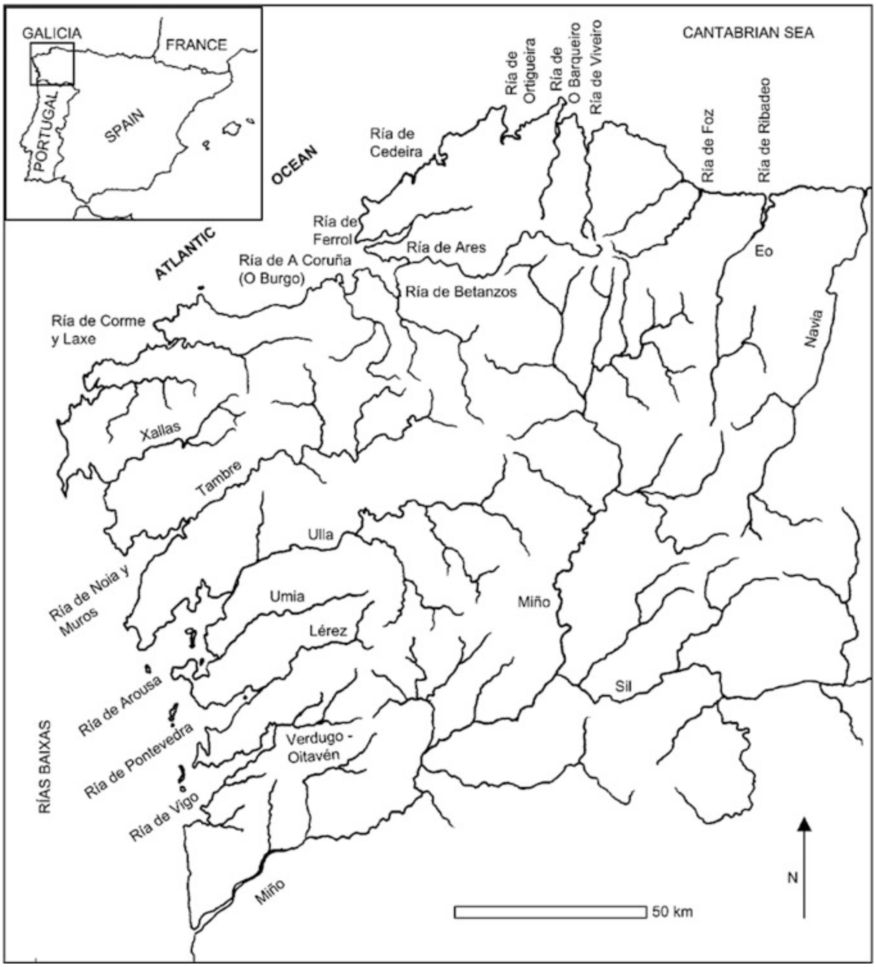


Fig. 17.1 Map of Galicia showing the rías along the coastline and the distribution of their hydrographic network (modified from Méndez and Vilas 2005)

17.3 Physical Processes

The movements of water masses and their variability in space and time are controlled by the balance between the tides, which in the coast of Galicia varies from 2 to 3 on the Atlantic shore, and up to 4 in the cantabrian coast area.

The mixing of fresh and seawater is a fundamental aspect in estuaries and rías, given that salinity gradually increases from the river towards the sea. In estuaries, this process may take place over a distance of dozens or even hundreds of kilometres, as occurs in the Gironde estuary (where it reaches 65 km) or in the Gambia River estuary (up to 200 km). In spite of the fact rías can extend more than 30 km

in length, for example the Ría of Vigo, these water mixing processes remain more restricted to the inner sectors.

Unlike in estuaries, wave action in rías constitutes one of the main processes that control the dynamics of the greater part of this environment. On the contrary, in estuaries, forcing mechanisms are fluvial discharge at the head and daily variations in sea level at the mouth. These differences are what bring about a different distribution of sediments on the bottoms (Vilas et al. 2005; Rey et al. 2005) and at the same time determine physical-chemical processes, which are characteristic in the fluvial-marine transition.

17.3.1 Wave Action

In the open sea, there are two types of waves: sea waves and swell. The first, which are characterised by isolated and irregular crests and a wide range of heights and periods, can appear in the inner areas of estuaries or rías; however, due to the limited dimensions of these areas, the height and period of the resulting waves are low. On the other hand, swell-type waves are able to exert an important effect due to the interaction produced between the wave and the bottom. Swell-type waves reach the coast with well defined fronts and wavelengths greater than their height, thus generating an orbital motion of the fluid particles, which reduce in diameter from the surface towards the bottom (Fig. 17.2). Whereas in deep waters this movement of fluid particles diminishes before reaching the bottom, when the swell approaches the coast, depth (h) is slowly reduced up to the point when the swell starts to feel the bottom (base level). This occurs when the wave depth and wavelength ratio is

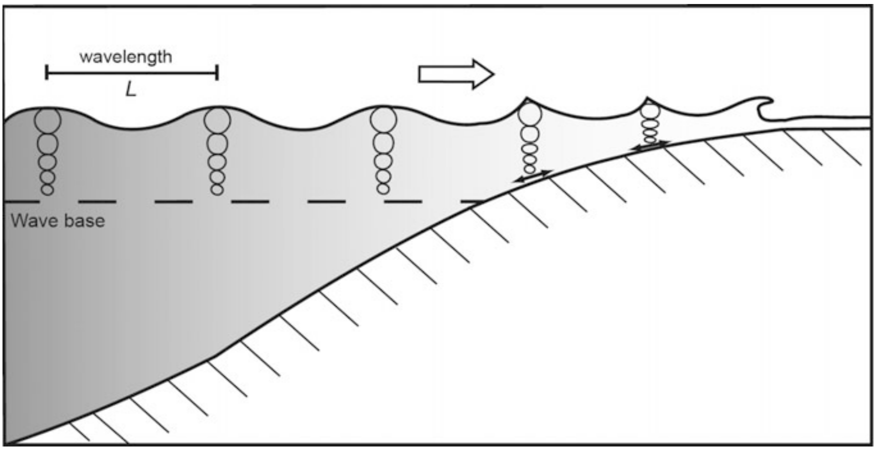


Fig. 17.2 Swell transition from deep to intermediate waters, showing the orbital movement of fluid particles as they approach the coast (modified from Vilas et al. 2010)

equal to or lower than 0.5. Under these circumstances, at depth, the circular orbit changes to elliptic and, at the bottom, the motion is limited to a back and forth motion. Swell energy increases as it moves towards the coast, and although in the case of estuaries it reaches its maximum at the mouth, in the case of rías, where the mouth is completely open and between 40 and 60 m in depth, swell is able to propagate without abatement almost up to the most internal areas, establishing different trajectories depending on the existing bathymetry.

17.3.2 Tides

Any tidal wave that reaches the coast and enters a semi-confined body of water in a coastal inlet, ría or estuary, generates a series of resounding effects which will modify the characteristics of the latter. These effects will be conditioned by two main parameters: the tidal prism and the cross-section of the estuary or ría basin. (The tidal prism can be defined as the volume of water between high tide and low tide that flows into and out of the estuary during the tidal cycle.) The variation of the area of said section together with the tidal prism will determine variations in the range of the tide and in the speed of the residual current in the basin of the estuary or ría. As the area of the basin diminishes due to the narrowing of the inner section nearer the head, the amplitude of the tide will increase and the current will intensify. This effect is offset by the gradual decrease in depth towards the head, which heightens the effect of the friction between the water column and the bottom. The behaviour of tidal waves in rías, given that the water column depth is much greater than the tidal range, corresponds to the hyposynchronic propagation model described by Le Floch (1961). On the other hand, in the inner most part it corresponds to the hyposynchronic type, because friction with the bottom and the margins of the basin bring about a reduction in the tidal parameters towards the river. Tidal processes in this area determine the mobilisation of sediments and their effect is often recognisable in sedimentary deposits. Similarly to meso and microtidal estuaries (Davies 1964), cyclical changes in the ebb and flow of the tidal currents may favour the resuspension of sediment from the bottom and the formation of the so-called turbidity maximum (Uncles and Stephens 1989). Recent works regarding the tidal effects on the external and central areas of rías (Rey et al. 2005; Vilas et al. 2005) have brought to light its limited influence on the transport of sediments and post-sedimentary processes. It is only in the inner most part, close to the mouths of the rivers, that the effect of the tide is clearly recognizable in the sedimentary deposits (Nombela et al. 1995).

17.3.3 Fluvial Discharges

The intensity and relative significance of fluvial currents decrease within the marine bodies of water that occupy the basins of the rías, as occurs in an estuary in the direction of the sea. This is due to the fact that the hydraulic gradient decreases in the area close to the river mouth. To this regard, the flushing capacity of fresh water or the outlet velocity in an estuary is a quantifiable parameter, which is based on the relationship between the annual average fluvial discharge and the transversal section of the area at the transition point of fresh and saline water (Gibbs 1977). The value of this parameter makes it possible to determine the landward intrusion limit of saline water and, consequently, the transition segment of the sedimentary sub-environments of the estuary.

Regardless of the discharge volume, fluvial currents are more significant in estuaries than in rías; they condition the longitudinal and transversal salinity gradients and therefore the density gradients, which in turn control estuarine circulation. They are also a source of sedimentary deposits.

17.3.4 Water Mixing and Estuarine Circulation

The interaction of fresh water and sea water in rías begins at the mouths of the river that flow into the rías. As a result of the difference in density between these two masses of water, a residual circulation is established, referred to as "estuarine circulation" (Dyer 1997), through which both water masses separate according to their different density: the denser (sea) waters below fresh river waters, as can be observed in estuaries. The velocity of the current is what determines the degree of the mixture between both, generating diffusion processes between them in the case of slow currents and more effective mixes for stronger currents. This variation in salinity not only generates a density gradient able to act as a driving force behind estuarine circulation; it also favours a series of physico-chemical flocculation processes and influences the formation of the turbidity maximum and the entrapment of fine particles from the middle of the ría up to the estuarine sector at the head of the ría.

In spite of the fact that the mixing and circulation processes in estuaries and rías are very similar, the differences that exist between the morphology of rías and that of estuaries bring about differences in the dynamic agents that dominate estuarine circulation. The mouths of estuaries are generally no deeper than 10 m, as a result only the tidal regime enables the entry of ocean water and the flow of fresh water towards the exterior predominates. The depth of rías, on the other hand, can be more than 50 m at their mouths, thus making it easy for a free and constant exchange of water mass and energy with the continental shelf (Souto et al. 2003).

17.4 Biogeochemical Processes

The variation in salinity from the river to the sea in rías, the same as in estuaries, is not only going to generate a density gradient that can act as a driving force behind estuarine circulation, but it also conditions a series of processes (flocculation, pelletisation, early diagenesis and methanogenesis) which are of interest in so far as recognizing the different sedimentary facies of these environments.

Flocculation by salts is a process which takes place whenever Van der Waals forces of attraction are involved. These forces are not particularly strong; nevertheless, their intensity varies inversely to the square of the distance between two particles of clay, and they eventually become important when said particles come close enough to each other. In fresh water, contrary to what happens in salt water, flocculation does not take place because clay particles are negatively charged and, when they come into close proximity, they repel each other because of their like charges. On the other hand, salt water contains free cations, which consequently interact with the negatively charged clay particles, thus reducing repulsion. In these conditions, the Van der Waals forces are able to overcome the repulsion forces. The formation of floccules will take place when the particles come into close enough proximity to each other.

The cohesive nature of the muddy sediments, which predominate in the central area of the rías and at the heads of estuaries, suggests that most of the sediment flocculates, except in extremely energetic conditions (Kranck and Milligan 1992). At present, it is known that particle flocculation is not an exclusively physico-chemical process, but rather a dynamically active process that can be easily modified by changes in hydrodynamic conditions (Manning and Bass 2006). Therefore, flocculation is also the function of the mechanisms that bring particles into contact, namely Brownian motion, turbulence (McCave 1985) and differential sedimentation (Manning and Dyer 1999) and of the mechanisms that bind them, which are salinity and the organic matter content (Van Leussen 1988). In some cases, the concentration can become so high that fluid muds are generated (an aqueous concentration of fine matter greater than 10 g/l). When tidal currents slow down, the sediment in suspension is deposited, creating a layer close to the bottom with a high concentration. If the dense suspension remains stationary, the basal part of the layer is consolidated in such a way that when the currents move faster again, they are not able to erode the material. The abundance and thickness of these muddy layers is directly related to the longitudinal variation of the matter in suspension. In the fluvial area, the concentration is low and the muddy layers are thin. Towards the sea, these layers are thicker and more abundant, due to the increase in the concentration of the matter in suspension; they reach their maximum just below the maximum turbidity peak.

As a result of the aforementioned mechanisms, the cohesive fine sediments can form a great range of aggregates known as floccules (Burban et al. 1989). Although they are less dense than the particles they are composed of, they sediment faster. As the floccules increase in size, their effective density generally decreases, but their

sedimentation velocity increases. Wave or tidal energy is often able to hinder the sedimentation of floccules; nevertheless, most of them sediment in the fluvio-marine transition.

In the central and inner parts of rías, in the same way as at the heads of estuaries, the muddy deposits are also made up of biodeposits, faecal pellets and pseudo faeces. Organic matter plays an essential role in the formation of these, by means of agglomeration or aggregation processes by filter feeders; they are then added to the flocculation processes and can form particles large enough to sediment the bottom. Most of the particles between 1 and 5 μm are ingested and after passing through the digestive tract, they are compressed and expelled into the water as compacted faecal pellets, the sizes of which vary in length from 50 to 300 μm. Some of the material is rejected before ingestion and expelled back into the water, constituting what are known as pseudofaeces. Many filter feeders, which inhabit these environments, such as copepods, tunicates, mussels and oysters, among others, transform the organic matter in suspension into pellets, the sedimentation velocities of which are much greater than that of the individual constituents. Many of the clay-organic pellets end up sedimented in areas of high velocity currents, zones where loose clays and floccules would not be deposited. The pellets are usually very resistant because the fine grain particles are very compacted and bound by mucus, on the other hand, the pseudofaeces are packed more loosely. These are very common processes in estuaries and in the central and inner areas of the Galician rías, where the cultivation of mussels on rafts contributed to the formation of the same (Rubio et al. 2001; León et al. 2004).

There are other biogeochemical processes which also play a key role in the recognition of different sedimentological facies in these transition environments, namely mineralogical and geochemical transformations that take place during early diagenesis. These are fundamentally controlled by the oxidation of the organic matter. This oxidation, or remineralisation, consumes the oxygen present in the interstitial sediment pore water. The size of these pores and their intercommunication diminishes with regard to the grain-size of the sediment. As a result, the renewal of oxygen in these muddy sediments takes place at a much lower rate than in sandy sediments, resulting in the generation of anoxic areas of high organic matter content.

Early diagenesis is very intense in muds with high organic matter content, which are typical in estuaries (Turner and Millward 2002; Bush et al. 2004) and rías (Rubio et al. 2001, 2011; Rey et al. 2005). In the latter, the deepening of the redox boundaries varies from inner to outer sector of the ría (Fig. 17.3). The oxic zone expands as it gets deeper toward the outer ría, in a similar way as the suboxic, anoxic and methanic zones. This spatial trend can be explained, either by a progressive change in the hydrodynamic conditions along the ría or by the different origin (terrestrial or marine) of the organic matter and their aging in the water column (Andrade et al. 2011) In these type of sediments, oxygen is depleted extremely quickly generally just scarce centimetres from the surface. Under these conditions, the sediment progressively acquires suboxic conditions, which eventually become anoxic as the oxygen disappears completely. However, the oxidation

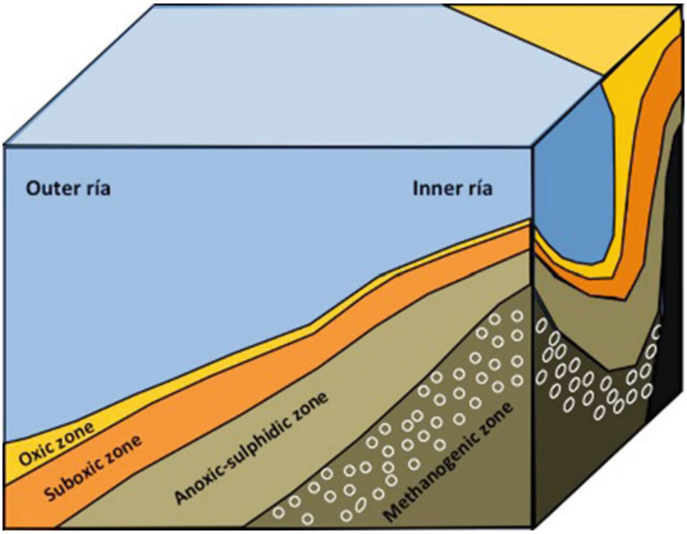


Fig. 17.3 Block diagram illustrating the deepening of the redox boundaries from inner to outer ría (modified from Rubio et al. 2011)

of organic matter continues with the use of alternative oxidants, with the intervention of bacteria, according to the general sequence described by Froelich et al. (1979), depending on their energy production. Therefore, the compounds used during the final stages of early diagenesis are sulphate and CO_2 dissolved in sea water. In so far as the first, the resulting product is sulphuric acid (H_2S); this compound reacts with the iron released during the dissolution of Fe oxides and oxyhydroxides and produces pyrite with a generally framboidal morphology. This mineral is not generated directly, but rather after a series of stages in which different iron sulfur-precursors intervene. First of all, monosulfides precipitate and are responsible for the blackish colour of these sediments. Afterwards, these evolve into greigite, pyrrhotite or mackinawite. These intermediaries are interesting in so far as the magnetic properties of the sediment, given that greigite and pyrrhotite exhibit a magnetic behaviour slightly less intense than that of magnetite. The results of these studies in the rías along the Atlantic coast have demonstrated that the concentration of magnetic minerals decreases rapidly with depth, until a very stable background value (Emiroglu et al. 2004; Mohamed 2006). This behaviour is related to the diagenetic dissolution of the detrital magnetic iron oxides and oxyhydroxides, with high dissolution rates of the same and a predominance of pyrites and greigites in the inner most areas of the rías (Rey et al. 2005), as well as Fe oxyhydroxides, oxides and silicates towards the exterior zone. These authors have determined half lives for the dissolution of detrital oxides such as magnetite of between 4 and 900 years in rías, depending on the type and content of organic carbon in the sediment (Emiroglu et al. 2004; Mohamed 2006).

During the last stage of the degradation of the organic matter, the reduction of CO_2 generates methane (CH_4), which accumulates in the sediments and can even form gas fields (Ferrín et al. 2003; García-García et al. 2003; Durán et al. 2007; Diez et al. 2007a; Ramírez-Pérez et al. 2015; De Carlos et al. 2017) of a considerable scale in the rías along the Atlantic coast (Arousa Ría 25.33 km^2, Vigo Ría 12.6 km^2, Muros Ría 11.5 km^2, Pontevedra Ría 4.54 km^2). This gas tends to accumulate in the most recent fine grain Quaternary sediments. The gas that escapes into the water column is known as ascending "plumes" and leaves pockmarks on the sedimentary bottom; these vary in size, between 5 and 10 m in the outer most areas and between 20 and 50 m in the more internal zones (García-García et al. 1999; Durán et al. 2007; García-Gil et al. 2015). Other processes can also bring about facies control on the accumulation and migration processes of the gas (Diez et al. 2007b; Vilas et al. 1999a). The levels of registered shallow gas and gas seepage, in the case of the rías along the Atlantic coast, present a similar spatial arrangement, characterized by a greater accumulation of gas in the inner and axial areas of the rías and of seepage along the edges of said areas.

Anthropic action is also reflected in the most recent sediments of rías and estuaries (Álvarez-Iglesias et al. 2006). On the one hand, an increase has been detected in the rate of sedimentation over recent years (Diz et al. 2002; Mohamed 2006; Álvarez-Iglesias et al. 2007), and on the other, most of the polluting heavy metals adhere to the muddy sediment particles (Rubio et al. 2000; Álvarez-Iglesias et al. 2003), which establishes an efficient process for their elimination from the water column. In the sedimentary record, the generation of anoxic conditions also has other important implications from an environmental point of view. When it comes to reducing or minimising the toxicity of trace metals, not only the formation of sulphurs (such as pyrite) in anoxic sediments, but also complexation by organic matter are both very important (Álvarez-Iglesias and Rubio 2008, 2012). However, when anoxic sediments oxidise, metals are released by sulfurs into the adjacent water column or into interstitial water and/or redistributed in other geochemical phases of the sediment; these metals can also interact with the benthonic fauna through their incorporation into tissue.

17.5 Zonation and Sedimentology

From a sedimentological and stratigraphic point of view, rías exhibit distinctive features of a unique sedimentation environment which is different from estuaries. Since the last Holocene transgression, the sedimentary filling found in the estuaries of these basins reveals a progressive transition towards the current conditions present in the rías (Fig. 17.4). Although the physical and biochemical processes acting in the rías are, to a large extent, similar to those present in different types of estuaries, thanks to their interaction with the existing geomorphological characteristics, it is possible to establish clearly differentiating elements. The most investigated in this regard (see references in Méndez and Vilas 2005) are the second

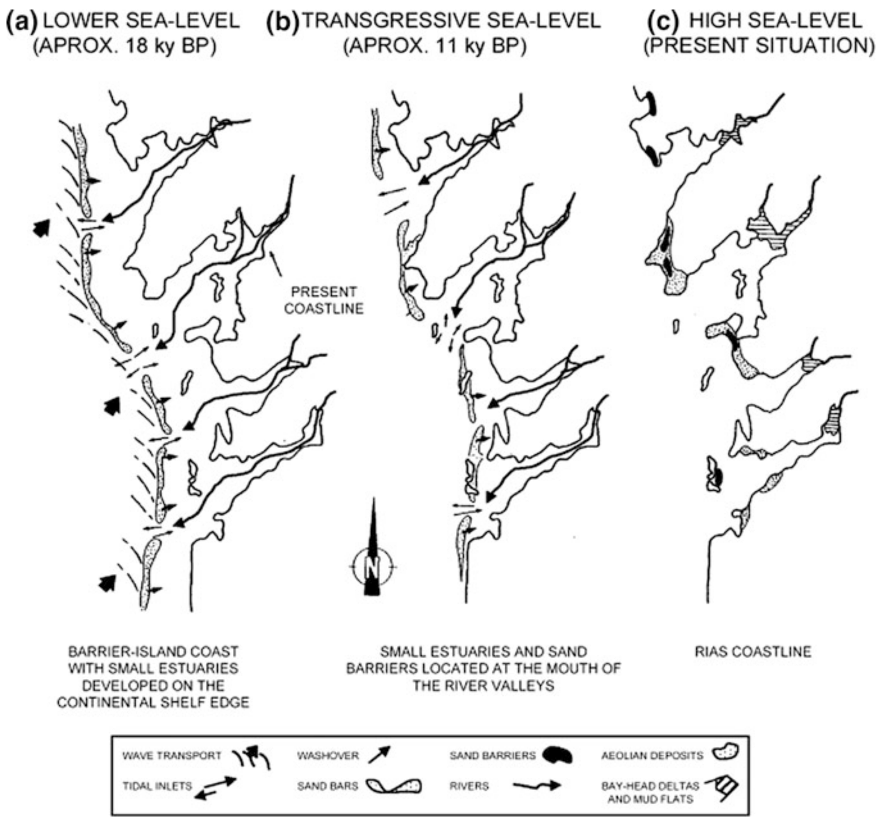


Fig. 17.4 Theoretical diagram showing the evolution of the coastline of the Rías Baixas in Galicia since the last sea-level transgression. Regression of the coastline since: **a** the Last Glacial Maximum (18 ky BP), **b** position during the Younger Dryas (11 ky BP) and **c** current location (modified from Vilas et al. 2010)

type, described by Nonn (1966) as those in which tectonic processes are responsible for their configuration. This type of ría matches those located along the Atlantic margin, known as the Rías Baixas (North to South: Ría of Muros-Noia, Arousa, Pontevedra and Vigo). This section and the following will pay greater attention to this part of the coast than to the more Northern rías or those along the coast of the Cantabrian Sea.

Seen from above, the Rías Baixas have a funnel-shaped morphology in which there are two distinguishable sectors; a larger cone corresponding to the ría itself, where the salinity of the waters is marine, and a smaller cone, which corresponds to the main fluvial channel discharging into the headwaters. Their orientation is approximately parallel to their longitudinal axis (e.g. the Tambre River in the Ría of Muros, the River Ulla in Ría of Arousa). Their surface areas vary between 140 km^2 (Ría of Pontevedra) and 330 km^2 (Ría of Arousa) and their length ranges from

20 km in the Ría of Pontevedra to 33 km in the Ría of Vigo; they are approximately between 8–12 km wide at the outer-most points and 1–3 km in the internal sector. Depths vary between 50–60 m at the outer-most points and 5–10 m in the inner-most areas. Geomorphologically, they are large valleys with a trough-like cross-section profile and flat bottoms with a slight slope towards the sea. All of them, except the Muros Ría, have islands at their entrances.

17.5.1 The Movement of Water Masses and the Distribution of Energy

In these rías, the movements of water masses have a mesotidal regime with a semidiurnal cycle (Alonso et al. 1993) and a maximum bottom velocity of around 15 cm/s (Souto et al. 2003), as well as oceanic coastal circulation (especially phenomena such as seasonal upwelling and downwelling). In winter, there is intense swell and significant maximum wave heights (H_{smax}) of around 8 m (Rey et al. 2005; Varela et al. 2005; Vilas et al. 2005); fluvial water flow is relatively unimportant and drainage basins are significantly small (<2500 km^2 surface area) and there are low average discharge rates (Ríos et al. 1992; Pazos et al. 2000; Pérez-Arlucea et al. 2005).

The general pattern of water mass circulation observable in the rías is very similar to what has been established for estuaries by several authors, not only in so far as salinity, but also in terms of water mixing (Pritchard 1967). Regarding hydrodynamics, it is possible to identify the main features of the typical estuarine circulation, with a considerable change to inverse estuarine or anti-estuarine during seasonal downwelling episodes (Varela et al. 2005). Although these circulation processes means that they tend to be associated to estuaries, their geomorphological characteristics, wide but deep "trough-shaped" valleys, contrary to what happens in estuaries, means that the effect of the propagation of tidal waves is limited within the whole area. This is due to the fact that the relationship between the tidal prism and the cross-section of the rías, and therefore the relationship between the convergence and friction of water masses with the bottom, which is so important in estuaries, is only relevant for the distribution of facies in the estuarine sector at the head of the ría, and in the Rías Baixas this area only corresponds to 20% of the depositional surface. As a result, in the remaining 80%, at the moment, typically estuarine facies distributions are not developed; sedimentary inputs are therefore depending on the distribution and transport capacity of the swell (Vilas et al. 2005, 2010). This variation of energy and its corresponding facies distribution (Fig. 17.5) is in contrast with that described by Dalrymple et al. (1992) for estuaries. Estuary zoning is characterized by high energy distribution at both extremes but low in the central area. In the internal part (proximal or head) and in the external part (distal or mouth), the energy of the river on the one hand and the wave action on the other, lead to coarse sedimentation being transported towards the central area. It is in the

latter where the energy is at its lowest and where the marine and fluvial influence are balanced out and fine sediments are deposited.

The distribution of energy in rías (Fig. 17.5a) is characterized by high swell energy initiated in open sea. It reaches the external part (distal or mouth) and moves progressively through the external and internal sectors of the ría, until the head of the ría or estuarine zone, where the marine and fluvial influences are balanced out. The fluvial influence is limited to this area, where the rivers discharging into these bodies of water lack sufficient energy to redistribute the coarser sediments that they deposit. The maximum tidal reach takes place at the limit between the inner ría area

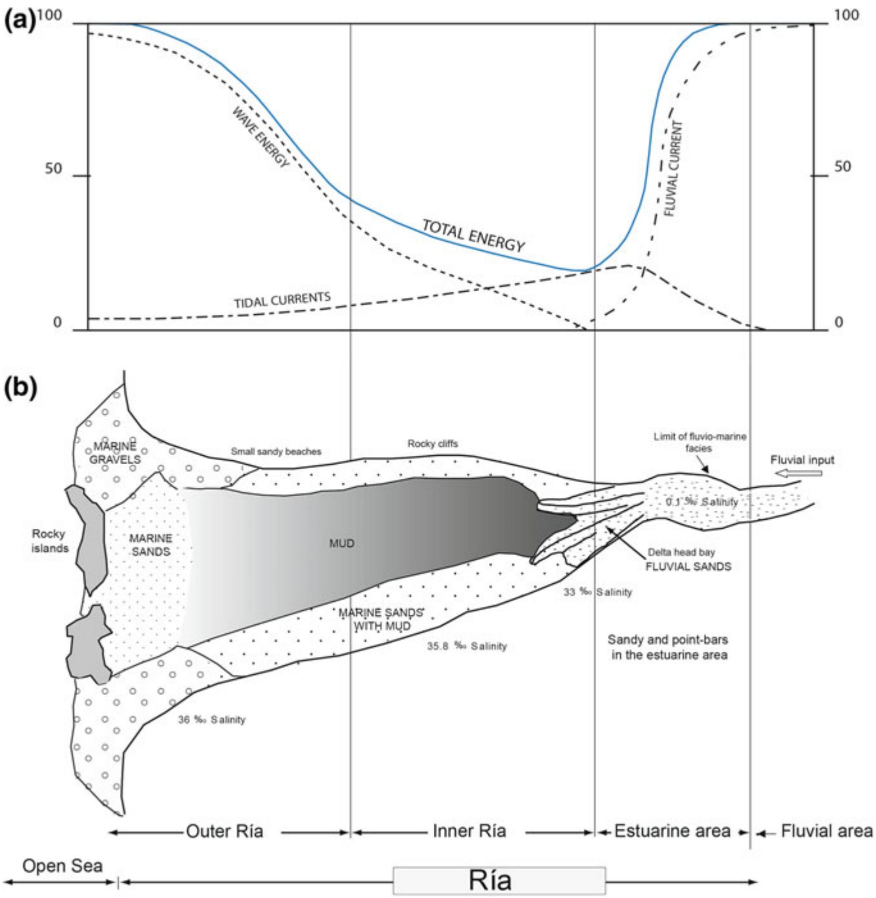


Fig. 17.5 Energy variation and facies distribution in the Rías (modified from Vilas et al. 2010): **a** Energy Variation: high wave energy at the mouth and in the external sector of the ría, progressively decreasing towards the internal sector of the ría. Fluvial energy of little importance in the estuarine zone at the head of the ría. **b** Facies Distribution: coarse marine sands in the distal part, passing to muddy sands and sandy muds, with high bioclastic content, in the outer and inner ría sectors. Estuarine mud with sand lenses and fluvial sands in the fluvial-tidal boundary

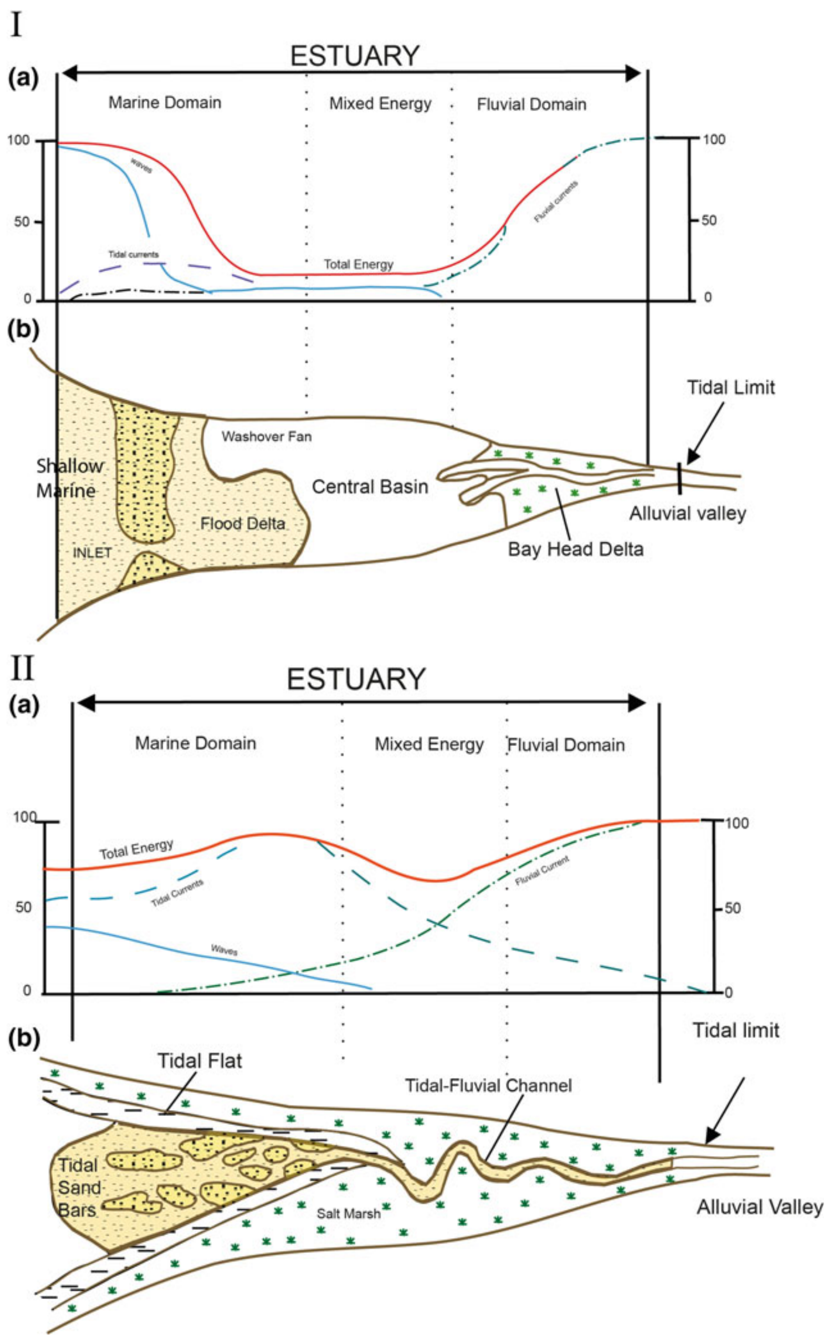
and the actual estuarine area, where it is possible to observe processes such as maximum turbidity and fine sediment accumulation due to changes in salinity and also flocculation. It is in this area, where swell energy is diminished, that the circulation can be classified as typically estuarine, as described for tide-dominated estuaries (see Fig. 17.6 II). The internal sector of the ría is dominated by waves and its action gradually increases toward the sea and it is here where the energy of swell-type waves is able to prevail over the tidal energy. The external area of the ría is clearly dominated by swell and eventually by the action of local processes, such as coastal outcropping. In this latter sector, with depths at the entrance reaching even more than 50 m, the distribution of energy towards the internal sector varies depending on the bathymetry; it is generally lower along the longitudinal axis due to the greater depth and more intensive towards the margins. Analyses carried out using numerical models establish that the swell in the internal part of the Ría of Pontevedra is concentrated along well-defined entry corridors (see Fig. 17.7); these vary depending on the swell conditions in open sea, mainly the wave period. The greater the period, the transition between deep and intermediate waters takes place at a greater depth (see Fig. 17.2). Therefore, the action of the swell will strengthen the turbulence and the mixing of waters and maintain the sediment in suspension in the exterior and internal sector of the ría.

In general terms, rías are exposed environments with an important tendency to preserve sporadic high-energy events, and where the main force, from a sedimentary point of view, is the wave energy. This fact is demonstrated in Fig. 17.8, that compares the textural trend of superficial sediments in the Vigo and Pontevedra Rías with that of an estuary, within the ternary diagram proposed by Fleming (2000), using the relationship sand/silt/clay as a basis. Keeping in mind the hydrodynamic model by Pejrup (1988) and Fleming (2000), the location of the data in this diagram reflects specific hydrodynamic energy conditions. The closer to the silt extreme, the greater the energy level. The presence of finer materials in the estuary (clay content up to 60%) is associated with lower hydrodynamic energy in the system, controlled by the balance between fluvial and tidal inputs.

17.5.2 Facies Distribution

The general distribution pattern of the sediments on the bottoms of the Rías Baixas reveals a longitudinal trend oriented lengthwise along their axes (see Fig. 17.5b), with wave-dominated facies, but an absence of features that are characteristic of those described for estuaries (see Fig. 17.6 I); these are restricted only to the internal area of the head (Nombela et al. 1995). This tendency is well represented for the partially open rías, due to the presence of islands at the mouth, but it can present slight variations if the entrance is completely open, as is the case in the Ría of Muros.

The finer sediments (silt and clay) extend from the internal part of the ría, occupying mainly the central basin (Vigo, Pontevedra and Arousa Rías) or sheltered areas on the northern shore (Muros Ría); they reach the external sector of the


I
ESTUARY
(a)
Marine Domain
Mixed Energy
Fluvial Domain
100
50
0
waves
Tidal currents
Total Energy
Fluvial currents
(b)
Tidal Limit
Washover Fan
Shallow Marine
Central Basin
Flood Delta
INLET
Alluvial valley
Bay Head Delta
II
ESTUARY
(a)
Marine Domain
Mixed Energy
Fluvial Domain
Total Energy
Tidal Currents
Fluvial Current
Waves
(b)
Tidal limit
Tidal Flat
Tidal-Fluvial Channel
Tidal Sand Bars
Salt Marsh
Alluvial Valley

◂**Fig. 17.6** Dynamic processes and major morphological components along the estuary (modified from Dalrymple et al. 1992). (I) Wave dominated estuaries: **a** high energy at the mouth, very distinct minimum in the central part and important fluvial energy at the head. **b** Characteristic "coarse-fine-coarse" facies distribution from the mouth towards the head. (II) Tide dominated estuaries: **a** tidal current energy dominating the mouth and longitudinal tidal bars breaking any existing wave energy. Decreasing fluvial energy downstream and energy minimum less defined than in wave dominated estuaries. **b** Characteristic "coarse-fine-coarse" facies distribution less defined than in wave dominated estuaries

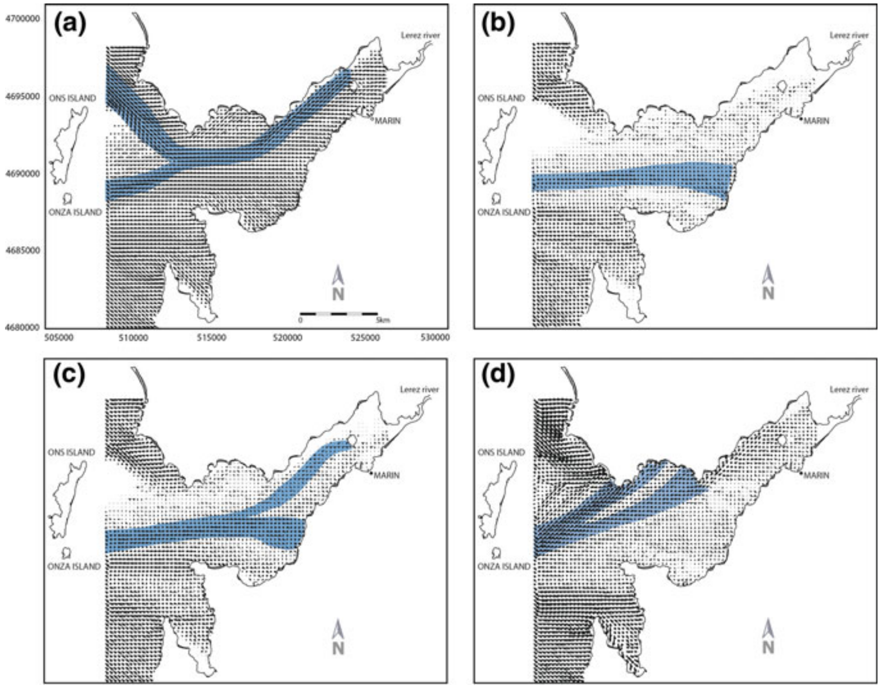


Fig. 17.7 Numerical simulation of wave propagation in the Ría of Pontevedra for the most frequent direction and different significant wave height (Ho) and peak period conditions (Tp): **a** Ho = 2.5 m, Tp = 14 s; **b** Ho = 3 m, Tp = 10.5 s; **c** Ho = 4 m, Tp = 12 s; **d** Ho = 6 m, Tp = 18 s (modified from Rey et al. 2005)

rías, where the sediments become coarser (sandy-silt, coarse sands and gravels) and only appear in deeper areas (between 20 and 50 m in depth). Organic matter is an important component of these sediments and reveals a distribution pattern coinciding with that of the muddy sediments that are more abundant in the central axis and in internal areas. This association is a consequence of organic matter being attracted to clay-like sediments, to which it is adsorbed and occasionally agglutinated, thus speeding up its decomposition. The concentration of organic matter, for example, in the sediments of the Ría of Vigo reaches very high values, between 2 and 10% (Vilas et al. 1995), especially if compared to deep-sea sediments, which

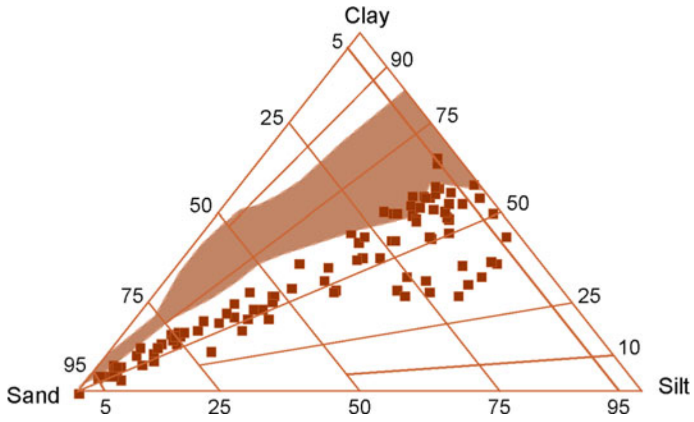


Fig. 17.8 Ternary diagram proposed by Fleming (2000) to assess the energy level of different sedimentation environments, based on the distribution of facies. The grey band represents estuary data (Dyfi Estuary, in Wales, UK). The dots correspond to sediment samples collected in the Rías of Vigo and Pontevedra (Galicia, NW Spain) (modified from Vilas et al. 2005)

are generally below 0.5%. This abundance is a result of the increased biological production in these rías, strengthened by the influence of coastal outcropping, which introduces nutrients into the rías and consequently promotes photosynthesis.

The predominant fauna in the rías is largely of marine origin. Only in the innermost areas, which are influenced by river contributions, is it possible to detect the presence of different communities than those found in saline waters. The influence of marine waters combined with contributions from the rivers, and the complex topography and bathymetry, determine the presence of a great sedimentary and environmental variability which has important biological consequences. Within a ría, we may find practically the whole range of coastal sediments, both within the intertidal and the subtidal zone (Vilas 2007).

In the intertidal mud flats areas, communities of species with a greater or lesser resistance to variations in salinity are abundant. These species are frequently sustained by the presence of marine phanerogams (*Zostera marina* and *Z. Noltii*), involving a highly interesting environment as they are particularly favourable zones for numerous infauna and epifauna species, spawning areas, juvenile refuges, sources of oxygen and organic matter.

Mud bottoms appearing in the inner areas and central areas of the rías are occupied by species, which may also be found in the open waters in wide sectors of the continental shelf. These include communities fundamentally dominated by surface and subsurface deposit feeder species. The predominating groups are polychaeta, such as Capitellidae (*Notomastus*, *Heteromastus*), the Maldanidae (*Euclymene*), crustacea and molluscs. Molluscs are a further dominant group within the muddy subtidal area, and there is an important presence of bivalves (*Nucula turgida*, *Abra alba*, *Pandora albida*, *Thysira flexuosa*, etc.). Small-sized

crustaceans are also particularly numerous, in almost all cases, the Amphipoda (*Ampelisca*, *Gammarous*) or Thainadaceae (*Apsweudes latreilli*).

The most exposed areas to the waves are characterised by sandy bottoms near the coast and shallow depths and they exhibit continuity with the beaches and gradually change to silty muds in central and deeper areas. In more sheltered areas, sands appear more dispersedly, resembling patches, between finer sediments. Moving inwards from the outer-most area, on both sides of the coastline that outlines the rías, there are low-energy sandy beaches located in areas partially or completely sheltered from ocean waves. These low-energy beaches characterized by calm conditions and minimal non-storm wave heights (Hsig −0.25 m) have received specific attention by several authors (Costas et al. 2005; Vila-Concejo et al. 2010; Bernabeu et al. 2012) since some studies revealed a different morphological behaviour from the open-ocean beaches (Short 2006).

These sandy bottoms are also densely populated by different organisms, both in the subtidal and intertidal environments. The type of community depends on the type of sands on which they settle: fine, medium or coarse grained, although as a general rule, the three types are dominated by polychaetae, molluscs, crustaceans and echinoderms, with an important presence of filter feeder species and surface deposit feeders. Although a large number of the species cited for silty bottoms may be present in sandy areas, (particularly where this is coarse-grained), certain species, which may be cited as characteristic of muddy bottoms, also appear here, such as molluscs of the family Cardiaceae (*Cerastoderma edule, Acanthocardia* spp., etc.) Veneraceae (*Venus striatula*, *Venerupis* spp.) and Tellinacea (*Tellina tenuis*, *T. fabula*).

Gravel appears at the mouths of the rías, which are controlled by swell. These sands and gravels are mainly made up of calcareous and siliceous bioclastic fragments, as well as minerals of siliciclastic origin, such as quartz, potasic feldspar, sodic feldspar, muscovite and biotite. Their abundance is greater towards the banks and in the more exterior areas, which are more exposed to swell action. In these areas, where there are mainly very coarse bioclastic fragments, the $CaCO_3$ content reaches values above 90% (Vilas et al. 2005). These fragments mainly comprise shell remains, although occasionally, patches of calcareous algae of the genus Lithothamnium are detected.

17.6 Evolution and Stratigraphic Interpretations

Rías constitute real sediment traps, where transgressive (TST) and highstand (HST) systems tracts are well represented (Durán 2005; Durán et al. 2007; Diez et al. 2007a); studies carried out confirm the tectonic-eustatic character of the Rías Baixas and their quaternary filling. The lowstand systems tract (LST) is not registered inside the rías due to the subaerial exposure of the entire continental shelf (Ferrín 2005), but it can remain in the deepest areas, between rocky outcroppings or distal parts of the continental shelf and/or on the edge of the slope. By means of

high-resolution seismic studies, several authors (Acosta 1982, 1984; Acosta and Herranz 1984; Herranz and Acosta 1984; Rey 1993; García-Gil et al. 1999, 2000; García-García et al. 2005; Durán et al. 2007; Diez et al. 2007a, b; Martínez-Carreño et al. 2017a) have offered a geometric vision and evolution of the sedimentary bodies; these are supported by the calculation of the thickness of the quaternary sediments over the basement of the rías, by the interpretation of sedimentary sequences and by the identification of paleoreliefs, particularly since the last glacial maximum (18,000 years BP). Consequently, the presence of granitic and metamorphic basements has been identified in the different rías and an important paleorelief has developed over these; over the latter, in turn, there are several units (Fig. 17.9). This studies and those realised by a multiproxy approach (Andrade et al. 2014) make it possible to obtain an approximate vision of the correlation between the evolution of the different stages of the rías filling and the relative changes in sea level documented in the Rías Baixas since the last glacial maximum. The oldest sedimentary filling is represented by a basal unit, which has been attributed to Pleistocene sediments of fluvial origin (Hinz 1970; Rey 1993; Durán 2005). The upper limit of the strata in this unit is interrupted by an important erosion surface generated during the subaerial exposure of the rías associated to the fall in sea level in the last glacial maximum, between 20 and 18 ky BP. It is estimated that at this moment, the relative sea level was around 120–130 m below the current sea level (Hanebuth et al. 2000; Dias et al. 1987, 2000; Rodrigues et al. 1991, 2000) and close to the edge of the current continental shelf. This unit is construed as estuarine successions developed during these periods of low sea level, prior to the last glacial maximum, equivalent to those described by Dalrymple et al. (1992) and Allen and Posamentier (1993). Over this last unit, there are several units that were deposited during different sea positions within the last eustatic cycle; they demonstrate a progressive variation in facies, not only vertically, but also horizontally, towards the internal part of the heads of the rías. It is even possible to define transitions from fluvial to estuarine facies, moving from the external sector towards the internal area of the rías, in a progressively rising sea. The presence of pockmarks and acoustic blankings, observed in many of the seismic records of the mid/internal sector of the rías, are proof of the accumulations of methane of microbial origin that are present in the sedimentary filling (Martínez-Carreño et al. 2017b). The origin of this gas seems to be related to the presence of the abundant organic matter contained in the intertidal mud flats and in the channels of the estuarine environments, which ended up sealed off by overlying units during the last transgression. Seismic records often reveal disorganized and chaotic facies in the deepest units, which turn into subparallel facies with more tubular geometries towards the surface (see Fig. 17.9); these represent a reduction of the energy gradient determined by the physiography of the basin and the reduction of the confinement of the sedimentation zone as the filling takes place (Diez 2007a, b). It is from this moment on that the V-shaped cross-section profile changes to a flat bottom "trough-shape", characteristic of the cross-section of rías.

There is scarce information regarding this type of environment, but in general terms, the ideal facies model could be considered the type described by Dalrymple

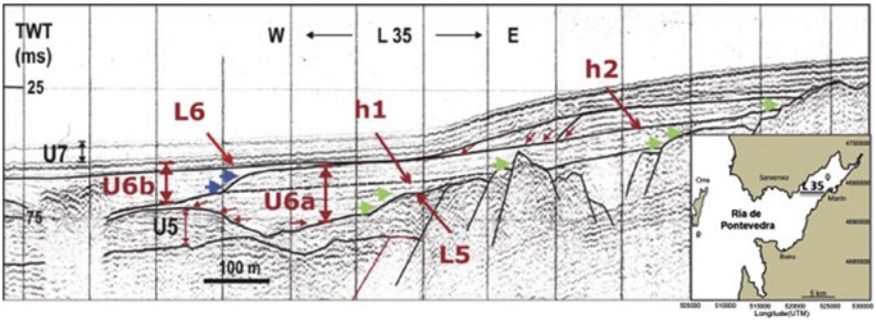


Fig. 17.9 Stratigraphic architecture of a seismic reflection profile (L-35) of the Ría of Pontevedra. The paleorelief (L5) represents the erosion surface originating on the basement or previous units, during the last glacial maximum (LGM) 18 ky ago, over which unit U5 is deposited followed by units U6 a, b. Its geometry is interpreted as being due to the global eustatic fall 11 ky ago (Younger Dryas), which brings about the partial erosion of the previous materials and it is over this paleorelief (L6) where the most recent unit (U7) is located, with the sea in progressive ascent. In the TST (U5 and U6) and in the HST (U7) sediments, numerous shallow accumulations of gas have been located (modified from Durán et al. 2007)

et al. (1994) as incised-valley systems, in which the fluvial incision has been produced over a former tectonic valley feature. Thus, over one complete sea-level cycle (sea-level fall to subsequent highstand) two main sedimentary sequences can be differentiated: the ría central basin and the estuarine zone.

The ideal sequence generated in the central basin of the rías is represented by an erosion surface underlying fluvial and estuarine-fluvial facies at the base, passing on to sandy/silt facies and/or silty/clay facies at the top of the sequence, depending on the variation of energy due to swell propagation (see Fig. 17.6) from the mouth to the more interior parts of the central basin of the ría. Due to these variations, the resulting differences that come about generate fining-upward sequences. These deposits can reach thicknesses of over 20 or 30 m because there is scarce erosive capacity, as the orbital movement of the swell does not reach the bottom. As mentioned above (see Fig. 17.2), whereas sediment is kept in suspension above the wave base level, below this the sedimentation of the finest sediments (silt and clay) is constant.

In the estuarine zone, the ideal sequence generated is similar to the one described by Dalrymple et al. (1992) for the bay-head delta of estuaries. In this sequence, as the estuary evolves and turns into a delta, there is a movement of facies towards the interior sector of the ría basin and an expansion of sandy bars interdigitated with intertidal mud flats and/or marshes with the development of tidal channels (Roy et al. 1980; Harris 1988). As a result, the fluvial and estuarine-fluvial facies at the base pass on to fluvial facies at the top of the sequence, generating a symmetric (fining upwards–coarsening upwards) sequence.

In the fossil record, the deposits of these types of environments, rías or estuaries, are not easy to interpret, given that they are often not formed by a single and simple

filling process. They have been reworked periodically, occupying the same spaces during several transgressions, and therefore any outcropping is very complex; neither is it easy to distinguish proximal from distal facies, which is essential for the vast majority of sedimentary interpretations, as suggested by Dalrymple and Choi (2007).

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